About to Crack

Los Alamos scientists are figuring out how to do

THE DATE WAS FEBRUARY 4th, 1975, and the setting was the city of Haicheng in northern China. On that day, the earthquake science community had a major breakthrough—for the first time ever, an earthquake of catastrophic proportions had been successfully predicted. Roughly a million people were evacuated beforehand and an untold number of lives were saved. There was just one problem: it was a fluke.

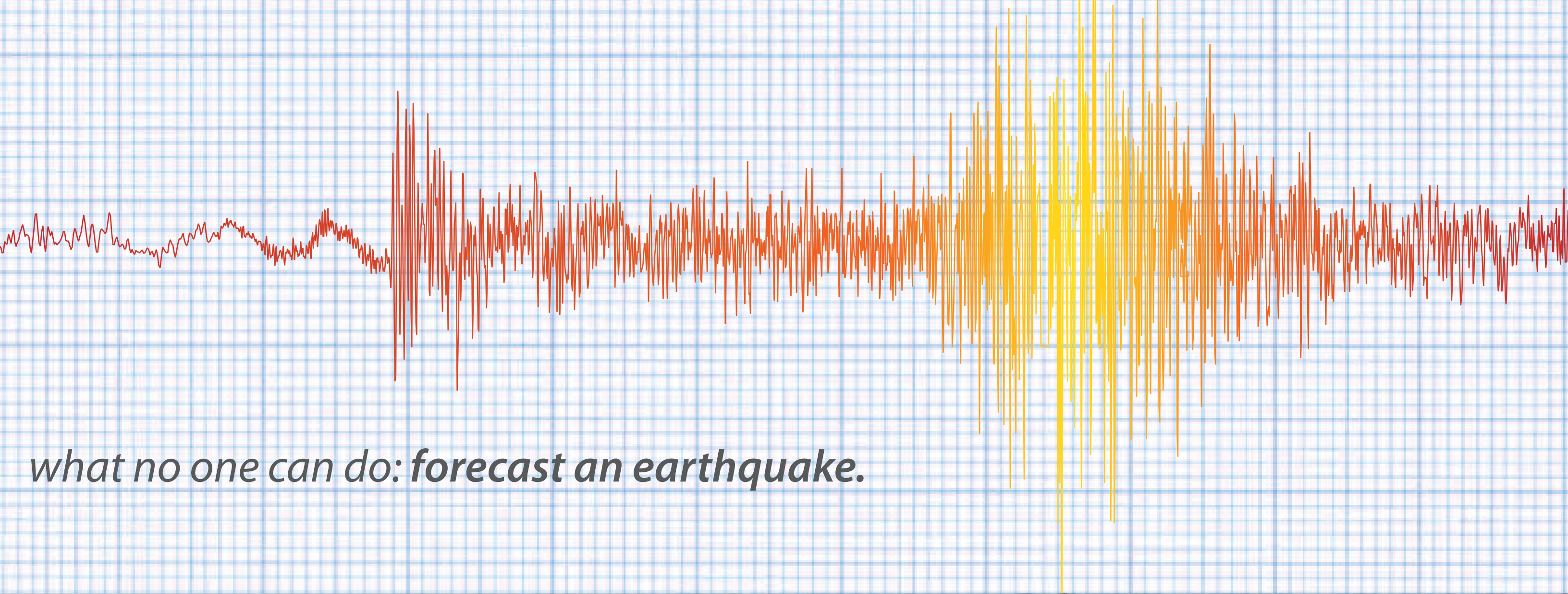
The prediction was the result of a combination of seismic rumblings (foreshocks), changes in well-water levels, and abnormal animal behavior. Based on these observations, state officials ordered a massive evacuation of Haicheng, and the next day a 7.3 magnitude earthquake shook the city, toppling empty buildings and filling empty streets with rubble and debris. The prediction was lauded as an extraordinary achievement, and shortly thereafter began the controversy. The methods failed to predict subsequent quakes and even 40 years later have yet to successfully predict another major earthquake.

Faulty faults

Earthquake scientists fall firmly into two camps: those who think all earthquakes are random events, caused by swirling thermal processes deep within the earth, and those who think that some quakes are actually triggered by others or are connected. Los Alamos geophysicist Paul Johnson is a member of the connected camp and believes that some earthquakes are triggered by seismic waves generated from far-off, previous earthquakes. He is studying what he describes as a modulating effect, in which earthquakes that eventually would have happened anyway (thermal swirling) actually happen sooner as a result of seismic perturbations from across the planet. By applying mathematical models and physical laboratory simulations, he and his collaborators want to understand how large earthquakes change the physical properties of the earth's crust and how these changes can lead to triggering of earthquakes in general—and temporal clustering of earthquakes in particular.

"Since the last turn of the century there have been about 15 really large earthquakes," Johnson says. "Are they all related?" He believes it's likely they are, and he's got the stats to back it.

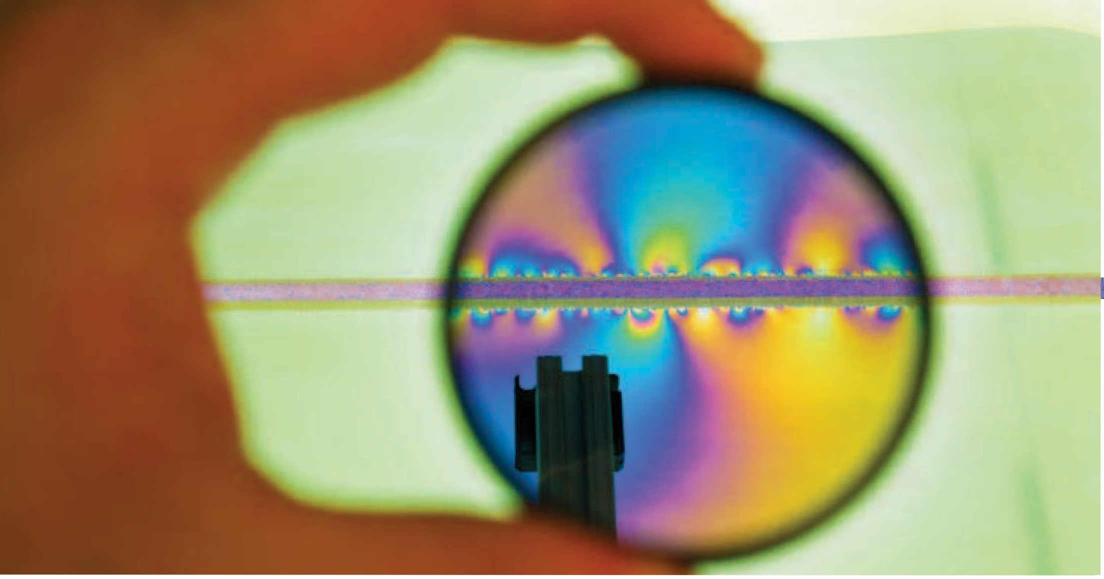
The surface of the earth, the watery and rocky layer within and upon which life exists, sits atop the deeper layers of crust and uppermost mantle, collectively referred to as the lithosphere. The earth's brittle lithosphere is broken into eight major tectonic plates (as well as myriad smaller ones), which are the basis of plate tectonic theory, the theory describing global geophysical processes such as continental drift and seafloor spreading. These plates are constantly moving and interacting, either sliding beneath one another in what is called subduction, or sliding past each other like opposing lanes of traffic in what is called lateral slipping. During these interactions, stress builds up along both sides of the fault (the interface of the two plates), and when the stress reaches a critical level, a slip event, or failure, occurs. If the failure is sudden, and the amount of built-up energy is large, an earthquake results.



what no one can do: ***forecast an earthquake.***

Johnson believes that seismic waves from large earthquakes temporarily decrease the elastic modulus of the weaker portions of the earth's crust—a measure of the ability of an object or material to resist stretching or compressing in response to being pulled apart or squeezed together. The decreased modulus, in effect a temporary softening of crustal material, extends over large distances, up to thousands of miles surrounding the fault, and preconditions additional faults within this range for accelerated failure. The extent to which the modulus is reduced and the time it takes to recover depend on both the strength and duration of the impinging seismic waves. As the perturbations generated from a very strong earthquake ripple through the land, toppling furniture and emptying cupboards, a similar degree of chaos occurs within the lithosphere. Small, medium, and large pieces of rock shift to energetically less stable configurations. Their unstable packing means they are in a state of increased interaction and decreased elastic modulus—thus perfectly charged to produce a quake.

Johnson and Los Alamos physicist Eli Ben-Naim, along with former postdoctoral researcher Eric Daub (now at the University of Memphis), have shown statistically that after a large quake, additional large quakes occur more frequently than a random pattern would predict. But the amount of data available from real earthquakes is severely limited because the seismic record only goes back about a hundred years and because data is only available after the fact, whereas the conditions *before* the quake are what are really important for establishing causation. To overcome these real-world limitations, Johnson's Los Alamos collaborators Scott Backhaus, Robert Ecke, and Drew Geller have



(Left) Viewed through a polarized camera lens, photo-elastic plates reveal discrete points of stress buildup along both sides of the modeled 2D fault as the far (upper) plate is moved laterally along the fault. (Right) The fault gouge is visible as tiny blue and red particles.

developed a 2D tabletop simulator that models the buildup and release of stress along an artificial fault. Using this experimental setup, they have compiled a virtual seismic record of quake events performed under precisely controlled conditions.

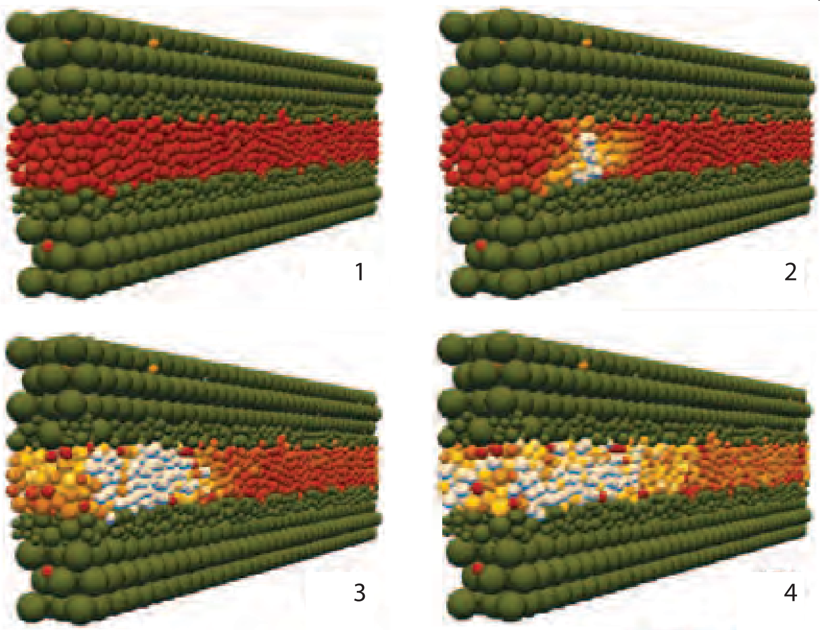
Therein lies the gouge

A key component of both natural and simulated faults is fault gouge. This is a vertical layer of granular material about 10–100 centimeters (cm) wide that fills the fault and is formed from the relentless grinding of tectonic plates against each other—like two sugar cubes being rubbed together, causing loose sugar granules to break free and accumulate. One of Johnson's major hypotheses is that fault gouge mediates the changes that lead to earthquake triggering. In the 2D experiments, the fault is 1 cm wide and 50 cm long, packed with small, vertically upright nylon cylinders (which would be spheres in a 3D system). Each cylinder is labeled with a tiny red dot or a tiny blue dot to indicate diameter (1.2 millimeters for blue, 1.6 millimeters for red)—this is the gouge.

During a simulation, the machine squeezes two horizontal "tectonic" plates of semi-rigid, plastic against each other laterally, with the gouge layer sandwiched in between them. Computer-controlled instrumentation applies a predefined amount of force to squeeze the plates together, compressing the gouge, and then slowly slides one plate laterally along the fault in a process called shearing that mimics the lateral slipping of real tectonic plates. The plates in the experiment also have tiny steel ball bearings glued to their upper surfaces adjacent to the gap. These detect the response of the semi-rigid plates to the forces of the gouge particles and also aid in measuring granular interactions and the size of quake events during experiments.

As the plates are sheared, the gouge is compressed and the particles rotate and shift, trying to find a more stable place to be, which in turn exerts pressure along both sides of the fault. The faster the plates are moving, the more pressure builds up; the more pressure builds up, the higher the elastic energy of the imminent failure. The whole apparatus is backlit so that cameras with polarizing lenses can capture images and videos of the shearing and slipping, and computers can determine the buildup and release of stress in terms of both magnitude and direction. This, then, tells the researchers where and by how much the elastic modulus is reduced, thus informing the forecast of future, triggered quakes within the same experimental setup.

To really understand how the gouge operates and participates in failure, the team uses 3D computer models in which the gouge is represented by spheres of various sizes. (True gouge particles are



Computer 3D modeling of gouge layer behavior during shearing. As the upper tectonic plate (top green layer) moves laterally with respect to the lower plate (bottom green layer) the movement of particles in the compressed granular layer (orange), is observed and measured. The lighter the color of the particle, the greater its speed. (1) No movement occurs during "stick phase," (2) localized movement occurs at the site of slip initiation, (3) as more gouge particles begin to move the slip spreads, and (4) extensive movement occurs in the granular layer as the slip propagates throughout the modeled fault.

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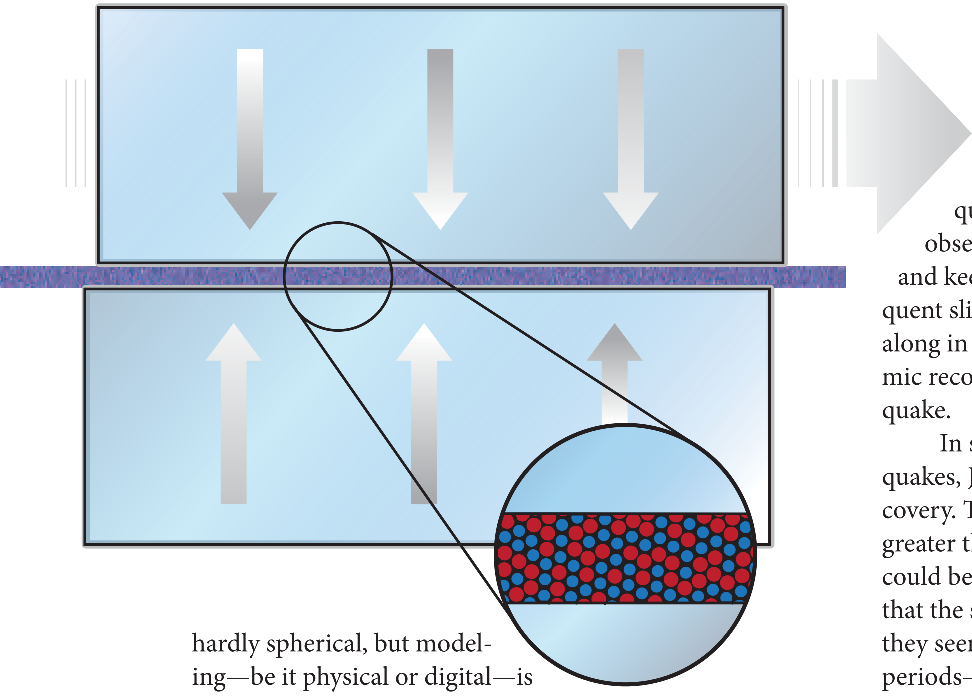
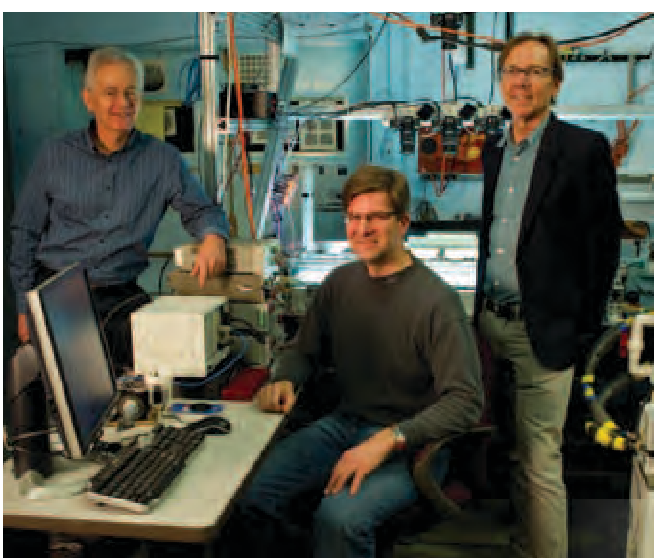


conditions correspond to either a spontaneous quake setup (no reduced modulus) or a triggered quake setup (reduced modulus), and the researchers observe how the gouge particles behave during shearing and keep records of the timing and magnitude of subsequent slips. Then, when the next large earthquake comes along in real life, they will compare it to this simulated seismic record to see if it looks like a spontaneous or triggered quake.

hardly spherical, but modeling—be it physical or digital—is all about approximation.) The computer models are used to develop templates, sets of conditions that reliably produce a particular result, which are then field-tested against real quakes. Data from a field site in Japan have recently shown that the models scale-up nicely. After the 2012 Indian Ocean earthquake, crustal disturbances exactly like those the templates predict were measured in Japan, approximately 2500 miles away. Just one other field site, this one closer to home (California), has the instrumentation required to test the templates; now it's just a matter of waiting—the researchers find themselves in the paradoxical position of rooting for a big one.

Trigger happy

Meanwhile, back in the lab, the experimental team has so far built a robust data set of spontaneous, isolated earthquakes that have been physically and digitally modeled. Now that they have determined how gouge behaves in a simple fault and what processes are associated with spontaneous earthquakes, the next step is to look at dynamic earthquake triggering—that is, when one earthquake induces another by setting the stage via less-stable packing. To simulate reduced elastic modulus of the earth's crust, as would be seen after a large earthquake, the force applied to the gouge from the plates in the 2D experiment is minutely increased. The input



In studying the historical record of very large earthquakes, Johnson and Ben-Naim made an interesting discovery. They looked at all great earthquakes (magnitude greater than 7.5) since 1900 and, after removing quakes that could be confirmed to be aftershocks of other quakes, found that the strongest quakes did not occur randomly. Rather, they seemed to be temporally clustered in two distinct time periods—mid-twentieth-century and the present. In other words, we may be currently in the midst of a connected series of triggered earthquakes. This is potentially bad news for humanity, but great news for science. But because the sample size is small, the statistical support is weak. However, with each new large quake the sample size grows by one, and comparison to Johnson's virtual seismic record becomes that much better at telling how accurate his team's models are—which, so far, is very.

In addition to modeling triggered earthquakes, the team would like to increase the complexity of their fault to better model a natural fault. What influence, for example, does the presence of groundwater in the fault have? Or what about a nonlinear fault with variable width? What about making the gouge more complex in terms of composition and particle size? It's no small feat to build a good laboratory fault experiment, and building one that can incorporate all these variables is still a ways off. So for now, 2D tabletop experiments and 3D computer modeling are where it's at—still leaps and bounds better than observing animal behavior and well-water levels.

This is the challenging reality of earthquake prediction. As Johnson says, "Forecasting is as good as it gets. It's doubtful we'll ever be able to truly *predict* earthquakes." But if he's right about triggering, and one good crack brings about another, then the theory of plate tectonics needs to be re-examined—specifically, the strong modulating influence of earthquake interaction. And there's a practical application as well, in hazard assessment and mitigation. Like the proverbial bad apple, one bad earthquake spoils the landscape for a whole bunch more—but knowing how quickly, how far, and for how long the bad apple's effects can spread may help to ease its bite. LDRD

—Eleanor Hutterer

Los Alamos scientists (left to right) Robert Ecke, Drew Geller, and Paul Johnson in front of their 2D tabletop experiment. By studying the interactions of granules within the fault, they are learning how earthquakes alter the earth's crust, preconditioning it for additional quakes.